

Potential for an argon directional dark matter detector

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We examine the additional physics potential for a large scale argon experiment that could also provide some information on the direction of the recoiling nucleus. We explore the statistical feasibility of directional signal detection using a simplified approach that categorizes events based on the vertical or horizontal orientation of nuclear recoil direction and with a likelihood-ratio statistical approach that discriminates directional signal against a possible isotropic background source.

I. INTRODUCTION

Dark Matter (DM) is one of the most compelling indirect evidence for physics beyond the Standard Model. It constitutes about 80% of the mass of the Universe [1] and has a fundamental role in the comprehension of the evolution of the Universe since the Big Bang. Understanding the nature of DM is therefore one of the most intriguing puzzles in physics. In the last decades many observational evidences have been gathered that could be explained by assuming a large amount of DM in cosmic structures at different mass scales. Starting from rotation curves of spiral galaxies [2], the most persuasive evidences come from the observations of anisotropies of the Cosmic Microwave Background [1], gravitational lensing on galaxy clusters [3] and galaxy scales [4], and the Big-Bang

nucleosynthesis [5]. A plausible model for DM is that it is constituted by non-relativistic Weakly-Interacting Massive Particles (WIMPs). In our Galaxy, the density and velocity distribution of this DM halo, which extends far beyond the visible disk, are inferred from the rotational curves of the visible matter [6, 7].

Direct detection DM experiments look for possible WIMP interactions with target nuclei aiming to detect an excess of WIMP-induced nuclear recoils above the estimated background [8]. Establishing this excess is a serious experimental challenge, given the expected electron and neutron backgrounds that mimic nuclear recoils from WIMPs and the low expected rate. It is necessary to remove radioactive backgrounds to a technologically-challenging low level and to rely on the detector capability to discriminate the remaining backgrounds. A non-directional detector could enhance the signal over background ratio using the expected annual modulation of the DM sig-

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nal due to the Earth motion around the Sun [9, 10]. For instance the DAMA collaboration [11] reported an observation of such a modulation. However, this seasonal modulation is expected to be smaller than 10% and background sources exist that have similar seasonal modulations.

A large mass detector with sensitivity to the direction of the recoiling nuclei would constitute a considerable breakthrough in the search for DM, as we shall argue in this work. A directional detector would have the capability of breaking through the so-called *neutrino floor* [12] and, if DM in the form of WIMPs is discovered, of opening the field of WIMP astronomy [13].

For the sake of concreteness a detector located at the latitude of the INFN Laboratori Nazionali del Gran Sasso (LNGS), Italy, is considered.¹ We show that the expected event rate varies by a large factor (4 – 8) when considering nuclear recoil directions going from the zenith to the horizon and, at fixed angular direction, it varies by about the same factor with sidereal-day period. The angular resolution of the detector is the ultimate characteristic that determines the experimental sensitivity to such a rate variation. The event-rate variations as a function of the sidereal time and as a function of the polar angle are very robust and are largely independent on details of the WIMP interaction and of the WIMP velocity distribution: they are direct consequences of the solar system motion through the Galaxy and of the Earth around the Sun. Isotropic backgrounds (*e.g.*: supernovae neutrinos), backgrounds from sources within the solar system (*e.g.*: solar neutrinos), or backgrounds with the periodicity of local day (*e.g.*: backgrounds that depend on the temperature or the atmospheric density) can be considerably reduced using such angular and time information.

Several prototypes of directional detectors exist [14, 15], generally based on the attempt to perform an imaging of the nuclear recoil trajectory. These detectors aim at achieving high spatial resolutions and are usually limited in mass, thus being capable to collect limited exposures. On the other hand, non-directional DM detectors have already reached exposures greater than 10^4 kg-day, [16–18] excluding spin independent WIMP-nucleon cross section lower than about 10^{-46} cm². Thus, it is important to pursue the design and study of a directional detector of the mass scale of many tonnes, able at once to collect an exposure of several tonne-years, and to add the directional sensitivity on the top of an already outstanding ability

to discriminate β/γ events and nuclear recoils induced by neutrons in favor of the unique selection of nuclear recoil candidates for WIMP interactions.

As argued in [19], a promising technique for a very large-mass detector with directional DM capability would be to exploit the phenomenon called *Columnar Recombination* (CR) in a noble liquid Time Projection Chamber (TPC). An argon-based detector sensitive to the effect of CR, would combine directional sensitivity with the ability to collect exposures of several hundreds of tonnes-year in a background-free mode [20].

In noble liquid TPCs the recoiling nucleus produces both scintillation and ionization. CR models [21] predict that the amount of signal due to ionization that can be collected in the presence of an electric field $\vec{\mathcal{E}}$ should depend on the angle θ_r between $\vec{\mathcal{E}}$ and the track (the average direction of the straggling nucleus). The ionization signal is expected to be maximal when $\theta_r = 90^\circ$, since electrons drift in a direction perpendicular to the region around the recoil track where ions are present, minimizing recombination. On the contrary, it should be minimal when $\theta_r = 0^\circ$, since electrons drift along the region where ions are present, with high probability of recombination. The ionization signal from the collected electrons would be a function of the component of the electric field perpendicular to the track, $\mathcal{E}_\perp = \mathcal{E} \sin \theta_r$, and, therefore would carry, together with the scintillation signal, information on the average direction of the recoiling nucleus. CR in a Liquid Argon (LAr) TPC would thus provide signatures for the orientation of the ionizing tracks relative to the direction of electric field. Evidence for this effect has been collected for α particles and protons [22, 23]. The SCENE experiment [24, 25], a small two-phase LAr TPC designed for calibration of nuclear-recoil responses, gave a hint for the same directional signature in the scintillation response of nuclear recoils of about 57 keV, approximately the energy at which, following the argument in [19], one might expect the ion range to be sufficient to form a track with a definite direction. However, the corresponding ionization response measured in SCENE did not show the same hint for a directional effect [25]. Therefore, a small prototype has been proposed with the aim to improve the SCENE measurement, as part of the DarkSide-20k proposal [26]. The DarkSide two-phase LAr TPC experiment, operating at LNGS, completed two DM-search campaigns [27, 28]. In the first campaign the central LAr TPC was operated with an atmospheric-argon fill; in the second with an underground-argon fill, with reduced content of ³⁹Ar. This second campaign demonstrated the ca-

¹ The LNGS coordinates are 42° 28' N 13° 33 E.

pability of underground-argon experiments at the scale of tens of tonnes to completely suppress β/γ background.

General aspects of DM directional detection have been discussed in a number of papers [29–32]. In the following, an exposure of 100 tonne-year is considered with a detector at LNGS as in the DarkSide-20k proposal [20]. At the location of the laboratory, the angle between the expected average WIMP direction with the vertical electric field in the LAr TPC spans the entire range between 0° and 90° during the day.

The paper is outlined as follows. Section II reviews the theoretical framework, introducing the formulae for the recoil cross section and rates as a function of the relevant angular variable, velocity distribution and coordinate systems. Section III presents the recoil angular distributions, while Section IV discusses the annual modulation of the signals. Section V presents a simplified statistical analysis method to study the DM directionality. We draw our conclusions in Section VI.

II. RECOIL RATES

A. Cross section and differential rates

In a given reference frame, let's assume \mathbf{v}_i is the velocity of the incoming WIMP of mass m_χ , \mathbf{u} is the velocity of the recoiling nucleus of mass m_N , $\mathbf{q} = m_N \mathbf{u}$ is the nucleus momentum and $E_r = q^2 / (2m_N)$ is the corresponding energy. The azimuthal and zenith angles of the recoiling nucleus are ϕ_r and θ_r , while ϑ is the angle between the incoming WIMP direction and the recoiling nucleus, as shown in Fig. 1. In general, recoil rates are convolutions of

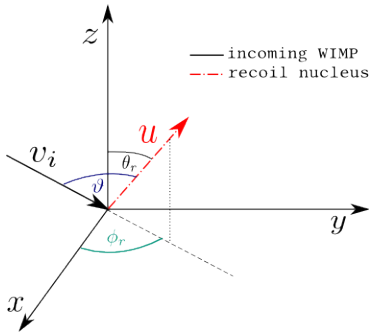


FIG. 1. Schematic view of a WIMP-nucleus scattering. The incoming WIMP with velocity \mathbf{v}_i hits the nucleus that recoils in the direction of the momentum $\mathbf{q} = m_N \mathbf{u}$ whose azimuthal and zenith angles are ϕ_r and θ_r . The angle between \mathbf{u} and \mathbf{v}_i is ϑ .

the scattering cross section and the incoming ve-

locity distribution. A point-like cross section in the center of mass is constant and can be parametrized by the total WIMP-nucleus cross section $\sigma_{\chi-N}$. For a spin-independent interaction with equal couplings for neutrons and protons, $\sigma_{\chi-N}$ can be expressed in terms of WIMP-nucleon cross section σ_n as $\sigma_{\chi-N} / \mu_N^2 = A^2 \sigma_n / \mu_p^2$, where A is the atomic mass and μ_N and μ_p are the WIMP-nucleus and the WIMP-nucleon reduced masses, respectively. The finite size of the nucleus is taken into account by introducing the Helm nuclear form factor [33]:

$$F(q) = \frac{3 [\sin(qr_N) - qr_N \cos(qr_N)]}{(qr_N)^3} e^{-(qs)^2/2}, \quad (1)$$

where $s = 0.9$ fm is the surface thickness and $r_N = 3.9$ fm is the argon nucleus effective radius.

In the frame where the target nucleus is at rest, the double-differential cross section depends on the cosine of the angle between the incoming WIMP and the recoiling nucleus $\hat{\mathbf{v}}_i \cdot \hat{\mathbf{q}} = \cos \vartheta$ as

$$\begin{aligned} \frac{d^2\sigma(q, \hat{\mathbf{v}}_i \cdot \hat{\mathbf{q}})}{dq^2 d\Omega} &= \frac{d^2\sigma(q, \cos \vartheta)}{2m_N dE_r 2\pi d\cos \vartheta} \\ &= \frac{\sigma_{\chi-N}}{8\pi\mu_N^2 v_i} F^2(q) \delta\left(\mathbf{v}_i \cdot \hat{\mathbf{q}} - \frac{q}{2\mu_N}\right). \end{aligned} \quad (2)$$

Given a velocity distribution for the incoming WIMP $f(\mathbf{v}_i)$, normalized so that $\int f(\mathbf{v}) d\mathbf{v} = 1$, and a WIMP mass density ρ , the double-differential recoil rate per unit mass, *i.e.* the rate per target nucleus divided by the nucleus mass m_N , as a function of the nuclear recoil energy, E_r , and of the recoil direction $\hat{\mathbf{q}}$ is

$$\begin{aligned} \frac{d^2R(E_r, \hat{\mathbf{q}})}{dE_r d\Omega_r} &= \frac{2\rho}{m_\chi} \int v \frac{d^2\sigma(q, \hat{\mathbf{v}} \cdot \hat{\mathbf{q}})}{dq^2 d\Omega} f(\mathbf{v}) d\mathbf{v} \\ &= \frac{\rho \sigma_{\chi-N} F^2(q)}{m_\chi 4\pi \mu_N^2} \int \delta\left(\mathbf{v} \cdot \hat{\mathbf{q}} - \frac{q}{2\mu_N}\right) f(\mathbf{v}) d\mathbf{v} \\ &= \frac{\rho}{m_\chi} \frac{\sigma_{\chi-N} F^2(q)}{4\pi \mu_N^2} \hat{f}(v_{min}, \hat{\mathbf{q}}), \end{aligned} \quad (3)$$

where $v_{min} = q / (2\mu_N) = \sqrt{2m_N E_r} / (2\mu_N)$ is the minimal WIMP velocity that can give momentum q or energy E_r to the recoiling nucleus and $\hat{f}(v_{min}, \hat{\mathbf{q}})$ is the 3-dimensional Radon transform [34] of the velocity distribution $f(\mathbf{v})$.

In this paper we assume the Standard Halo Model (SHM), *i.e.* an isotropic Maxwell-Boltzmann WIMP velocity distribution of width σ_v in a reference frame at rest with respect to the Galactic center. In a reference frame with velocity \mathbf{V} relative to

the Galactic center, the velocity distribution is

$$f(\mathbf{v}) = \frac{1}{\sqrt{(2\pi\sigma_v^2)^3}} \exp \left[-\frac{1}{2} \left(\frac{\mathbf{v} + \mathbf{V}}{\sigma_v} \right)^2 \right] \quad (4)$$

and the corresponding Radon transform is

$$\hat{f}(v_{min}, \hat{\mathbf{q}}) = \frac{1}{\sqrt{2\pi\sigma_v^2}} \exp \left[-\frac{1}{2} \left(\frac{v_{min} + \hat{\mathbf{q}} \cdot \mathbf{V}}{\sigma_v} \right)^2 \right]. \quad (5)$$

Therefore, if recoils are measured in a frame at rest with respect to the center of the Galaxy, $\mathbf{V} = 0$ and the rate is isotropic. Similarly, when measured in a frame at rest with respect to the Sun, \mathbf{V} is the Sun velocity relative to the galactic center \mathbf{V}_{SG} , which points towards the galactic coordinates [35] ($\ell_c=90^\circ$, $b_c=0^\circ$), roughly the direction of the Cygnus constellation, and has magnitude $V_{SG} \approx v_0 = 220$ km/s, where v_0 is the Galactic orbital speed at the Sun position. For an Earthbound laboratory the velocity \mathbf{V} can be decomposed as $\mathbf{V} = \mathbf{V}_{SG} + \mathbf{V}_{ES}$, where \mathbf{V}_{ES} is the Earth velocity relative to the Sun, which has magnitude $V_{ES} \approx 30$ km/s, about ten times smaller than v_0 . The laboratory velocity relative to the Earth center has been neglected, since it is almost two orders of magnitude smaller than \mathbf{V}_{ES} .

If a detector collects events of energy $E_{th} < E_r < E_{max}$, the direction-dependent recoil rate per unit mass, obtained by substituting the Radon transform from Eq. (5) in Eq. (4) and integrating over the energy range, becomes

$$\frac{dR(E_{th}, E_{max}, \hat{\mathbf{q}})}{d\Omega_r} = \int_{E_{th}}^{E_{max}} dE_r \frac{d^2R(E_r, \hat{\mathbf{q}})}{dE_r d\Omega_r}. \quad (6)$$

The study presented in this paper focuses on the use of polar detectors *i.e.* detectors that give only information on the angle θ_r between the recoil track and a fixed axis. If the fixed axis is the vertical direction, the relevant recoil rate is

$$\frac{dR(E_{th}, E_{max}, \cos\theta_r)}{d\cos\theta_r} = \int_0^{2\pi} d\phi_r \int_{E_{th}}^{E_{max}} dE_r \frac{d^2R(E_r, \hat{\mathbf{q}})}{dE_r d\Omega_r}, \quad (7)$$

which, after integrating out ϕ_r , depends on $\cos\theta_r$. In addition, if a detector cannot distinguish signals from recoil tracks differing by 180° , events that differ by 180° are summed together. The relevant rate

is the so-called “folded” angular recoil rate:

$$\frac{dR_F(|\cos\theta_r|)}{d|\cos\theta_r|} \equiv \frac{dR}{d\cos\theta_r}(\cos\theta_r) + \frac{dR}{d\cos\theta_r}(-\cos\theta_r), \quad (8)$$

which depends only on $|\cos\theta_r|$. Dependences of the recoil rates on other variables are not shown.

Unless explicitly stated, this work shows results for a LAr detector using the reference values $m_\chi = 200$ GeV, $m_N = 0.923 A$, where A is the argon atomic mass, $\rho = 0.3$ GeV cm $^{-3}$, and $\sigma_v = v_0/\sqrt{2}$. Rates are given for a reference cross section $\sigma_n = 10^{-46}$ cm 2 , which is of the order of the limit set by the LUX and PANDAX-II collaborations [16–18], for recoil energies from $E_{th} = 50$ keV 2 to $E_{max} = 200$ keV, and for an exposure of 100 tonne-year. Note that the anisotropy of all rates in Eqs. (6), (7), and (8) depends only on the velocity \mathbf{V} . In a given frame, which fixes \mathbf{V} , one can choose different angular coordinate systems. If the angular coordinate system is time dependent, *e.g.* a coordinate system fixed to the rotating Earth, the direction of \mathbf{V} in that system becomes time dependent. In a frame at rest with respect to the Earth and using Galactic coordinates, \mathbf{V}_{SG} is constant and only \mathbf{V}_{ES} rotates with the annual periodicity of the Earth revolution. Since \mathbf{V}_{ES} is an order of magnitude smaller than \mathbf{V}_{SG} , the WIMP apparent direction $-\mathbf{V} = -(\mathbf{V}_{SG} + \mathbf{V}_{ES})$ rotates with annual periodicity around the fixed \mathbf{V}_{SG} direction with an opening angle of about one tenth of radiant. In this frame the peaked angular distribution is the main signature of the signal and allows for background reduction. In the laboratory coordinate system, the coordinates and, therefore, the apparent direction of \mathbf{V} makes an additional rotation with the periodicity of a sidereal day and an amplitude that depends on the latitude. This specific periodicity is also a characteristic signature and provides more background suppression.

B. Recoil rate in Galactic angular coordinates

Figures 2 and 3 show results in a reference frame at rest with respect to the Sun in Galactic coordinates to demonstrate the potentialities of a directional detector independently of the location, as it has been extensively done in the past, and to discuss the influence of the threshold energy E_{th} . All other results will be given for a detector located at

² This choice for the threshold energy is motivated by hints from the SCENE experiment [25] for directional dependence in the scintillation signal at energy of 57.3 keV.

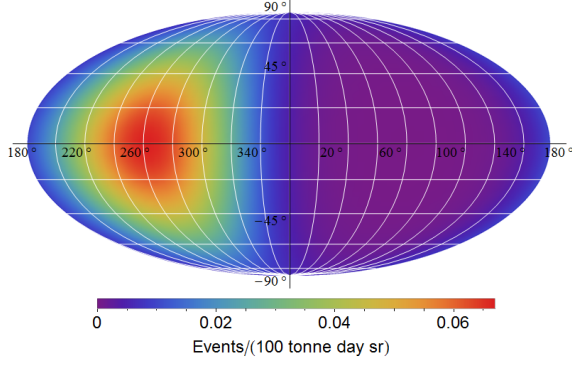


FIG. 2. Directional recoil rate in argon, Eq (6), on a Mollweide equal area projection map of the celestial sphere in galactic coordinates. The horizontal axis is the galactic longitude $0^\circ < \ell < 360^\circ$ and the vertical axis is galactic latitude $-90^\circ < b < 90^\circ$. The WIMP mass is 200 GeV, the WIMP-nucleon cross section 10^{-46}cm^2 , the energy interval ($50 \text{ keV} \leq E_r \leq 200 \text{ keV}$), and the total exposure is 100 tonne-year. The color scale is units of events/(100 tonne \cdot day \cdot sr).

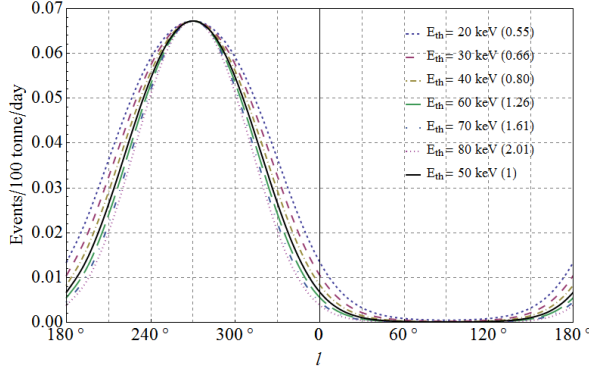


FIG. 3. Directional recoil rate in argon as a function of the galactic longitude l in degrees when the galactic latitude $b = 0^\circ$; the corresponding angle θ_r between the recoil and the Sun direction is $\theta_r = \ell - 270^\circ$. The WIMP mass is 200 GeV, the WIMP-nucleon cross section 10^{-46}cm^2 , the total exposure 100 tonne-year and the recoil energy is integrated between E_{th} and 200 keV, where $E_{th} = 20, 30, 40, 50, 60, 70$, and 80 keV. The number of events per day can be directly read on the vertical scale for the solid curve ($E_{th} = 50 \text{ keV}$): the other curves have been rescaled to have the same maximum. As shown in the legend the rescaling factors are: 0.55, 0.66, 0.80, 1, 1.26, 1.61, 2.01, respectively.

the latitude of LNGS in the local coordinate system with the polar axis pointing in the vertical direction. Indeed, the potentialities of a directional detector and, more specifically, the signature in the angular recoil rate of the detector motion through the WIMP halo are best illustrated in Galactic coordinates in a frame at rest with the Sun. In this

coordinate system, \hat{x} points from the Sun towards the Galactic center, \hat{y} in the direction of the Solar motion and \hat{z} towards the Galactic north pole; therefore, $\mathbf{V} = v_0 \hat{y}$. In Figure 2 we show the angular recoil rate of Eq. (6) for argon on a Mollweide equal area projection map. The horizontal axis is the galactic longitude $0^\circ < l < 360^\circ$ (the counter-clockwise angle from the \hat{x}) and the vertical axis is the galactic latitude $-90^\circ < b < 90^\circ$ ($90^\circ - b$ is the angle from the \hat{z}).

The recoil rate is clearly anisotropic [30] and points at coordinates ($l = 270^\circ, b = 0^\circ$) opposite to the direction of the Sun motion throughout the Galaxy. Since the expected signal in the SHM is rotationally symmetric around the Sun direction, the width of the forward peak is better shown on one dimensional plot as a function of the galactic longitude l (Fig. 3). Figure 3 shows that the width of the forward peak can be reduced by selecting a higher threshold energy, even if the width of the peak is dominated by the WIMP velocity distribution. Indeed, in a liquid the straggling of the recoiling nucleus will broaden the peak. A higher threshold lowers the total rate as it can be quantitatively seen from the normalization factors.

III. RECOIL DIRECTIONAL SIGNALS AT LNGS

In this section we consider WIMP scattering in a reference frame at rest relative to a detector situated at LNGS with the \hat{z} axis along the vertical. In this frame we call the angle between the recoiling nucleus and the vertical axis θ_r . In particular we study the expected rates, Eqs. (6) and (8), as function of $\cos \theta_r$ and of the time of the day. The effect of finite angular resolution is also considered.

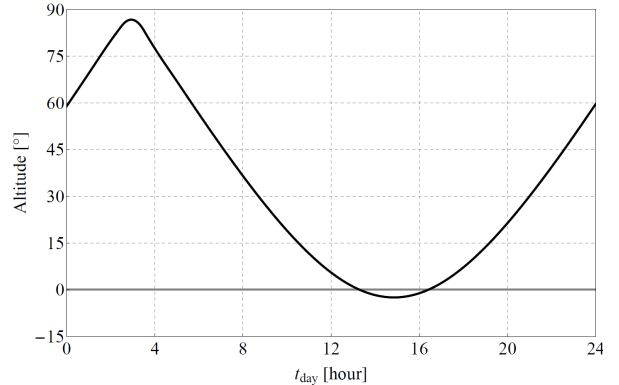


FIG. 4. Altitude (angle from the horizon) of the Cygnus constellation as seen at LNGS as a function of the time. The horizontal line at 0 corresponds to the horizon.

Figure 4 shows the Cygnus constellation altitude

at the LNGS location as a function of the time from the midnight of the summer solstice, providing a clear picture of the daily dependence of the expected recoil *average* direction.³ As the cross section in Eq. (3) peaks in the forward direction, when Cygnus is close to the zenith nuclei recoil mainly towards the nadir, and when Cygnus is close to horizon nuclei recoil mainly in the horizontal plane. The most important qualitative feature in Fig. 4 is that Cygnus spans the whole range of polar directions from zenith to horizon during the day at the LNGS latitude, thus allowing a strong correlation between time and polar angle of the recoils. Since the Cygnus polar angle period is the sidereal day, this correlation is lost during the year if local solar time is used.

A. Differential rates as functions of the polar angle

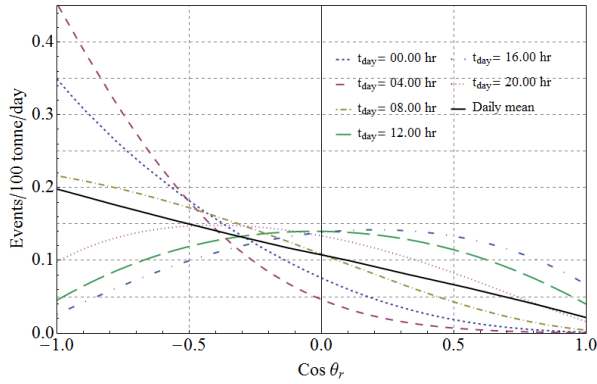


FIG. 5. Differential recoil rate as a function of the cosine of the polar angle θ_r at the latitude of LNGS. The y axis shows the number of events per day in a argon detector with a 50 keV energy threshold for a WIMP-nucleon cross section of $\sigma_n = 10^{-46} \text{ cm}^2$, and a total exposure of 100 tonne-year. The solid curve is the daily average, while the other six curves show the rate at times of the day four-hour apart.

Figure 5 shows the differential recoil rate, Eq. (7), as a function of $\cos\theta_r$ for different times of the day and the daily average. The average rate is more than twice as high for negative values of $\cos\theta_r$ than for positive values, since Cygnus is most of the time above the horizon. In addition, there is

a strong dependence on the time of the day: the asymmetry in $\cos\theta_r$ is larger when Cygnus is high in the sky, *e.g.*, at hour 4, while it is smaller when it is close to the horizon, *e.g.*, at hour 16.

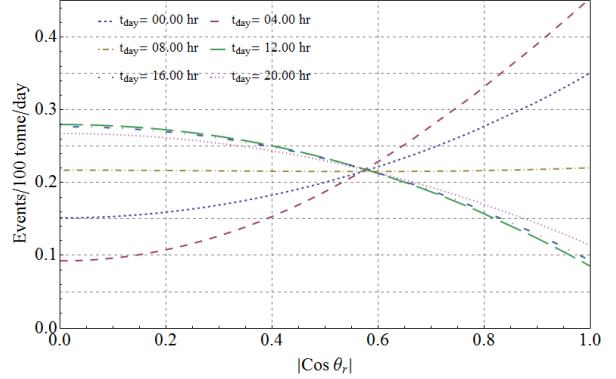


FIG. 6. Same as figure 5 for the “folded” rate in Eq. (8).

Figure 6 shows the “folded” differential recoil rate introduced in Eq. (8), the relevant rate for a polar detector. The angular and time dependences of the rate remain quite strong even without the information on which side of the track the head is. When Cygnus is close to the zenith (horizon) the rate is peaked at $|\cos\theta_r| \sim 1$ ($|\cos\theta_r| \sim 0$).

B. Vertical and horizontal event categories

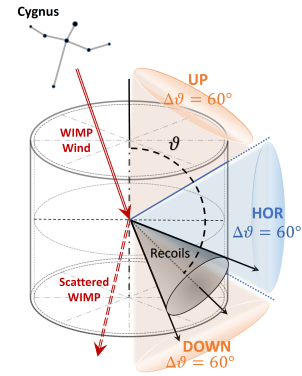


FIG. 7. Schematic view of the two categories in which events are divided, namely horizontal (HOR) and vertical (VER=UP+DOWN) events.

A simple and robust analysis of the time and angular dependency of the event rate of WIMP collision is achieved by separating the candidate event sample into two categories that require only a minimal amount of angular information. Events can be categorized as horizontal events (HOR), defined by

³ As already discussed the correlation between the Cygnus direction and the WIMP wind changes by at most a tenth of radian during the year because of the Earth revolution around the Sun.

$|\cos\theta_r| < 0.5$ or $60^\circ < \theta_r < 120^\circ$, and vertical events (VER), defined by $|\cos\theta_r| > 0.5$ (see Fig. 7). Rates due to isotropic background sources should give an equal number of events in these two equal solid angles.

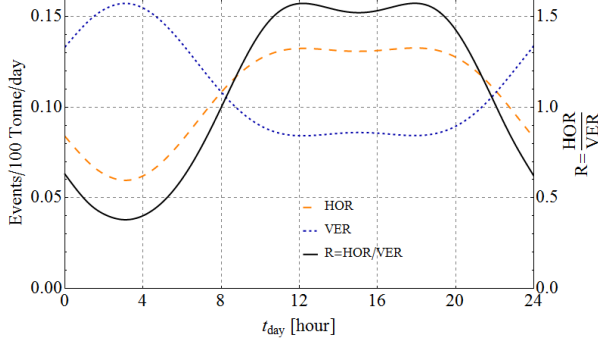


FIG. 8. Horizontal (HOR), corresponding to $|\cos\theta_r| < 0.5$ or $60^\circ < \theta_r < 120^\circ$ (long dashes) and vertical (VER), corresponding to $|\cos\theta_r| > 0.5$ (short dashes) event rates as a function of time in event per 100 tonne per day (left scale). The solid line shows the ratio $R = \text{HOR}/\text{VER}$ (right scale).

Figure 8 shows horizontal and vertical WIMP event rates as function of the time of the day. At the latitude of LNGS, the time signature of an anisotropic WIMP wind is evident in spite of the very crude angular classification. In the same figure we also show the ratio $R = \text{HOR}/\text{VER}$ of horizontal to vertical events. This ratio which is constant and equal to unity for an isotropic signal, is useful to analyze the signal anisotropy and its time dependence: It is independent of the overall normalization and provides some cancellation of other systematic effects. For the given choice of parameters, R changes during the day by a factor of about 4.

IV. SEASONAL EFFECTS

As already discussed in Section II A, the Earth velocity within the Galaxy and, therefore, the velocity relative to the average WIMP velocity $\mathbf{V} = \mathbf{V}_{SG} + \mathbf{V}_{ES}$ changes during the year due to the annual rotation of orbital velocity \mathbf{V}_{ES} . Since $|\mathbf{V}_{SG}| \approx 220$ km/s and $|\mathbf{V}_{ES}| \approx 30$ km/s with an angle of about 60° between \mathbf{V}_{SG} and the ecliptic, the module $|\mathbf{V}|$ changes by about $\pm 15/220 \approx \pm 7\%$ during the year causing a similar change of the WIMP flux, while the annual change of direction is about a tenth of radiant. This annual change of the average WIMP speed produces a corresponding change of the total daily rate, which reaches its maximum around the end of May and its minimum around

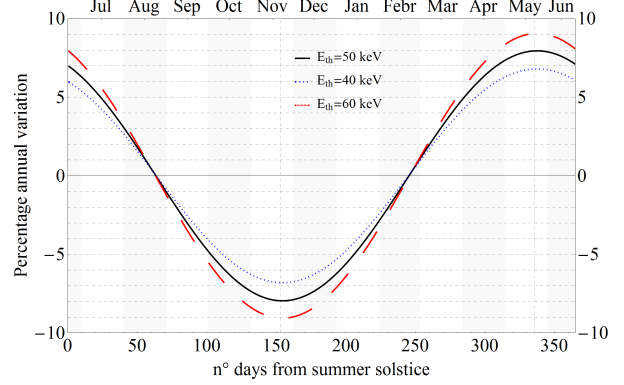


FIG. 9. Percentage annual variation of the argon detector event rate as a function of the number of days from the summer solstice for three different recoil energy thresholds. The solid line corresponds to $E_{th} = 50$ keV, the dotted line corresponds to $E_{th} = 40$ keV, and the dashed line corresponds to $E_{th} = 60$ keV. The corresponding average daily rates are 0.27, 0.20, and 0.15 events per day for a total exposure of 100 tonne-year.

the end of November, as clearly visible in Fig. 9 for three threshold energies: $E_{th} = 40, 50$, and 60 keV. As expected [36, 37] the larger the energy threshold the larger the percentage annual modulation.

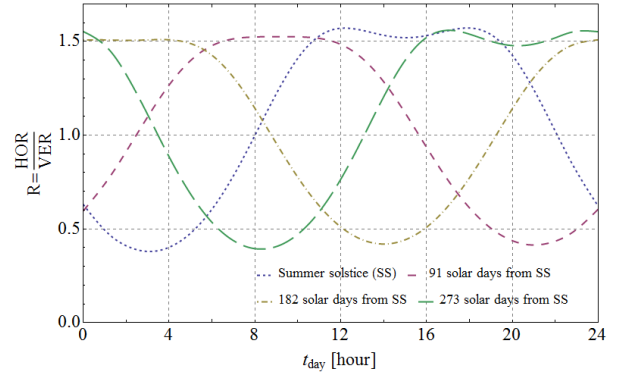


FIG. 10. Ratio R of expected number of events along the horizontal and the vertical direction in an argon detector located at LNGS as function of the time of the day at four different days of the year. R is defined in Fig. 8 and in the text referring to it.

Figure 10 shows the daily variation of the ratio R at four times of the year; the signal time structure changes during the year as function of the local time. Cygnus, *i.e.* the WIMP direction, returns exactly in the same position in the sky after a sidereal day, which is about four minutes shorter than the solar day. This annual drift of the angular signal as a function of the solar time can be used to characterize the WIMP signal with respect to other effects that also produce daily variations but with

solar-day periodicity [38].

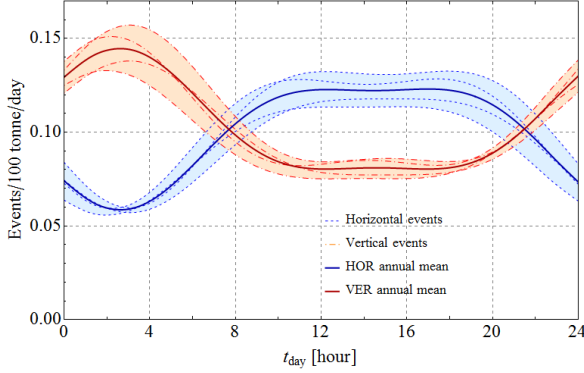


FIG. 11. Daily variation of horizontal ($\text{HOR} \equiv |\cos \theta_r| < 0.5$) and vertical ($\text{VER} \equiv |\cos \theta_r| > 0.5$) event rates at four different days of the year. The solid lines represent the average of the HOR and VER as described in the text.

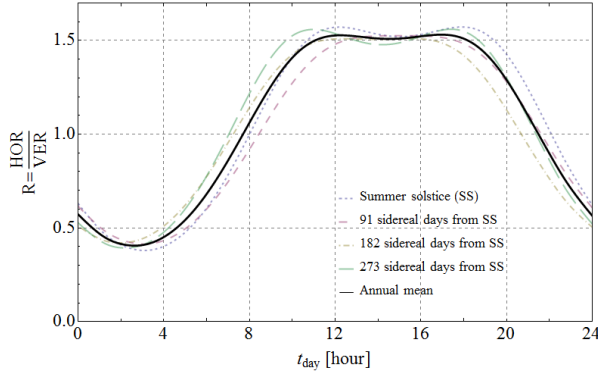


FIG. 12. Same as Figure Fig. 11 for the ratio $R = \text{HOR}/\text{VER}$.

If the sidereal time is used to time-stamp events, the annual drift is eliminated and it is possible to compare and average events rates taken at different days. Figure 11 shows the HOR and VER event rates taken at four times of the year and the annual averages computed by considering coincident times differing by an integer number of sidereal days, where HOR and VER have been defined in Section III B.

Figure 12 shows for R the same information as Fig. 11 for HOR and VER. Note that part of the seasonal variation of HOR and VER cancels out in their ratio R .

The much larger time variation of the directional signal relative to the seasonal variation of the non-directional signal is evident by comparing Fig. 9 to Fig. 12, or also in Fig. 10 or Fig. 11 by themselves.

V. STATISTICAL ANALYSIS FOR A DIRECTIONAL SIGNAL

A path through the discovery process of DM searches may proceed initially through the observation of a number of candidates that significantly exceed the small expected background level. However, after rejecting the background-only hypothesis, the study of angular properties of the observed nuclear recoils can corroborate the belief that the observed signal can be attributed to DM interactions. We want to quantitatively discuss the number of events necessary to discriminate the hypothesis of a DM signal with preferential incoming direction from the Cygnus constellation against the alternative hypothesis of an isotropic signal.

Since the tens of events that are needed for testing the directionality of the signal are already sufficient to achieve a large statistical significance of the DM signal against a small number of expected background events, the statistical analysis of the recoil directionality does not need to reach the “ 5σ ” level by itself to provide a convincing proof of a WIMP signal.

The negative logarithm of the likelihood ratio is taken as test statistic t to discriminate between the hypotheses of a directional signal from the Cygnus constellation (Cyg) against an isotropic signal (iso) (\mathbf{V} as in Section II A or $\mathbf{V} = 0$, respectively). Such test statistic can also be extended in order to take into account the effect of systematic uncertainties for realistic applications [39]. The test statistic is defined as

$$t(\vec{x}^{(1)}, \dots, \vec{x}^{(N)}) = -\ln \frac{\mathcal{L}_{\text{Cyg}}(\vec{x}^{(i)})}{\mathcal{L}_{\text{iso}}(\vec{x}^{(i)})}, \quad (9)$$

where $\mathcal{L}_{\text{Cyg,iso}}(\vec{x}^{(i)})$ are the likelihood functions corresponding to the two hypotheses. Given a sample of N independent WIMP events, the two likelihood functions are given by the products of the probability density function (PDF) values $f_{\text{Cyg,iso}}(\vec{x}^{(i)})$ corresponding to each WIMP interaction candidate:

$$\mathcal{L}_{\text{Cyg,iso}}(\vec{x}^{(1)}, \dots, \vec{x}^{(N)}) = \prod_{i=1}^N f_{\text{Cyg,iso}}(\vec{x}^{(i)}), \quad (10)$$

where the vector $\vec{x}^{(i)}$ contains the variables used to characterize the event (i) . In the present work we use the two variables θ_{rec} , the recoil polar angle in the laboratory, and θ_{Cyg} , the polar angle of the Cygnus constellation at time of the event in the laboratory: $\vec{x}^{(i)} \equiv (\theta_{\text{rec}}^{(i)}, \theta_{\text{Cyg}}^{(i)})$. Additional variables such as the recoil energy or the time of the year

could provide additional information and, in principle, better discrimination between the two hypotheses, our conclusions are conservative in this respect. The same method can be used to study alternative models for WIMP distribution or backgrounds.

The PDFs $f_{\text{Cyg,iso}}(\vec{x}^{(i)})$ have been sampled generating 10^{10} simulated interaction recoils for each hypothesis and binning the allowed kinematic range of each variable $\theta_{\text{rec}}^{(i)}$ and $\theta_{\text{Cyg}}^{(i)}$ with 100 bins. In the simulation the energy has been smeared by 10 keV in order to account for the energy resolution and an energy threshold of 50 keV has been used. In addition we compared the case of perfect resolution of the recoil angle in the laboratory frame to a resolution smeared by a Gaussian distribution with a 400 mrad width.

Given an assumed number N of WIMP interaction candidate events, 10^7 pseudo-samples of N events each were generated for each of the four cases, namely events from Cygnus direction or isotropic and with the two angular resolutions. The test statistic, t , of Eq. (9) has been evaluated for each pseudo-sample and stored into histograms with a fine binning. Figure 13 shows the distribution of the test statistic t defined in Eq. (9) for the case of ideal (top panel) and 400 mrad resolution (bottom panel) with $N = 50$. The directional (isotropic) distribution is peaked at negative (positive) values. The expected p -value is computed from the distribution of the test statistic t_{iso} corresponding to the null (isotropic) hypothesis by considering the percentage of pseudo-sample with t below $t_{\text{Cyg},0}$, where $t_{\text{Cyg},0}$ is the median of the distribution of the test statistic t_{Cyg} corresponding to Cygnus direction hypothesis. The corresponding one- or two-standard-deviation excursions are calculated by considering instead of $t_{\text{Cyg},0}$ the boundaries of the one- or two-standard-deviation interval for the test statistic t_{Cyg} . The expected p -values as a function of the observed number of DM interaction candidate events are shown in Fig. 14 for ideal angular resolution (top) and for a 400 mrad resolution (bottom). In the case of an ideal resolution, a 3σ evidence of a directional signal is expected to be achieved with about 100 candidate events, while about 50 events are sufficient for a 2σ significance. For an angular resolution of 400 mrad, a 3σ evidence can be achieved with about 250 events, and 100 events allow a 2σ significance.

VI. CONCLUSIONS

We have discussed how a directional argon detector located at LNGS could provide a very clear

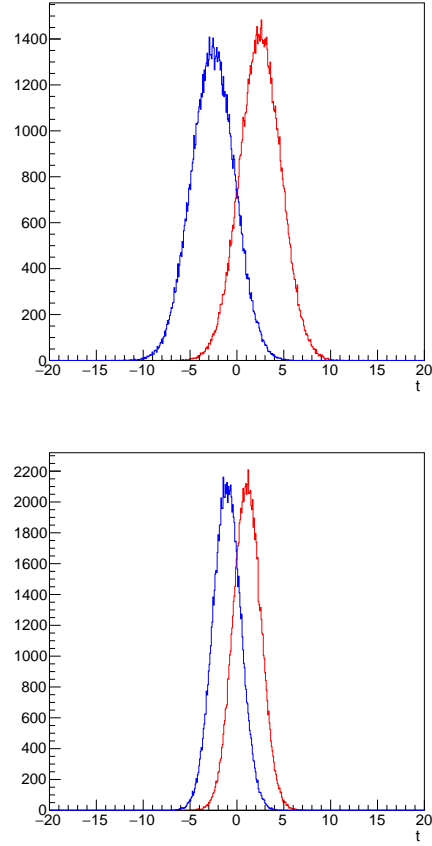


FIG. 13. Distribution of the likelihood-ratio test statistic t for ideal resolution (top) and for a resolution of 400 mrad (bottom) for $N = 50$ observed DM candidates. The blue (red) curves that peak at negative (positive) values of t correspond to the hypothesis of incoming particles from the Cygnus direction (of isotropic signal).

signature for WIMP signal. While a statistical method based on a likelihood-ratio test can exploit the entire angular information present in a data sample of WIMP collision candidate events, the directional signature remains quite strong even if the angular information is determined separating events into two categories only containing horizontal and vertical events.

A study based on a simplified parametric simulation shows that a directional detector could exclude an isotropic background hypothesis at 90% confidence level with a few tens of candidate events, depending on the achieved angular resolution. Namely it could reach a significance level of the directional signal exceeding 3σ with about 100 events in case of ideal angular resolution, or about 250 events for an angular resolution of 400 mrad.

In view of the evidence presented in this paper, and in consideration of the strong exclusion

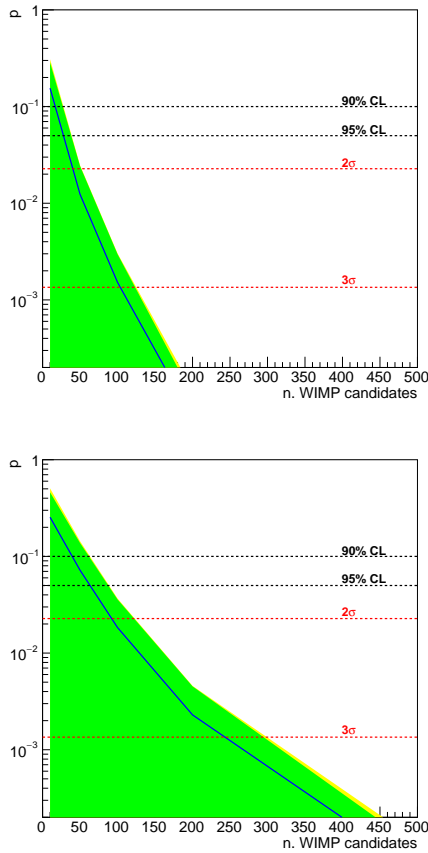


FIG. 14. Expected p -value (blue line) of the null hypothesis (isotropic signal) as a function of the observed number of DM interaction candidate events for ideal resolution (top) and for a resolution of 400 mrad (bottom). The green and yellow bands show the excursion range at one and two standard deviations. The horizontal lines show from top to bottom the 90% and 95% CL exclusion and the 2σ and 3σ significance levels.

bounds already achieved by null observations performed by non-directional dark matter detectors, it is of utmost importance the development of experimental technologies able to couple directional sensitivity with large fiducial masses (many tonnes) and the ability to collect large exposures free of background from β/γ events and neutron-induced nuclear recoils. One possible avenue would be offered by the presence of the signature of columnar recombination in nuclear recoils in a liquid argon time projection chamber, where this effect has already been observed for α particles and protons. Dedicated experiments performed on monochromatic, pulsed neutron beams will allow to explore the possible presence of this signature.

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